THE PLASMA CONNECTION

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A Few Recent Contributions of Low Temperature Plasma Science to Human Welfare

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Plasma science has a long history of contributions to the promotion of human welfare. As one example, plasma lighting (such as high pressure Hg, Na, and metal-halide lamps) has illuminated urban expressways and rural highways, stadiums, airports, and other public spaces worldwide for almost a century, and the fluorescent lamp was the gold standard of the lighting industry for more than six decades. Germicidal lamps, based on a low-pressure discharge in Hg/Ar mixtures, serve to this day as an effective and non-chemical disinfectant in hospitals, clinics, assisted-care facilities, and residential and commercial air purification systems.

A more recent example of the impact of low temperature plasma science on human health is that of plasma medicine in which diffuse atmospheric plasmas have proven to be remarkably effective in the treatment of wounds and infections, in particular. In that regard, two research groups at the University of Illinois are pursuing the treatment of ear infections in humans (known as otitis media (OM)). More than 80% of all children in the United States will suffer from at least one ear infection, and one of the challenges in treating ear infections is that the bacteria responsible for OM reside in the middle ear cavity in a biofilm, a secreted extracellular matrix that harbors the bacteria. The prescription of antibiotics is a common treatment for OM, but has been shown to be ineffective in >30% of cases involving acute OM. In addition, the antibiotic dosages required have raised concerns in the medical community about the rising resistance of children (and adults) to many of the most effective antibiotics.

The approach of the Illinois team is to determine if excited species, radicals, and other chemically-reactive atoms and molecules produced in a plasma are able to traverse the human eardrum, and to do so in sufficient quantities to inactivate the bacteria responsible for an infection. Of equal concern is the potential interaction of these reactive species with the eardrum itself and, specifically, the imperative that the plasma not harm the eardrum in any way. If the fluence of reactive atoms or molecules reaching the biofilm and bacteria within is sufficient to disrupt the biofilm matrix but the eardrum is impacted negatively, the process is of little clinical value. Motivated by earlier studies exploring the disruption of biofilms formed in municipal and residential water distribution systems with atmospheric pressure plasmas, the Illinois researchers conducted initial experiments, described in *npj Biofilms and Microbiomes* (7, 48 (2021)), which employed a thin cellulose substitute (phantom) for the human eardrum. It was found that plasma treatment times of 20 minutes or less were able to deactivate the bacterial strain *Pseudomonas aeruginosa* to the extent that the dosage of antibiotics necessary to eradicate infections was 2-4 orders of magnitude below those prescribed normally. That is, the impact of the plasma treatment is to disrupt the biofilm and inactivate or weaken the bacteria and, thus, make it considerably more vulnerable to the antibiotic. An artist's rendition of a modified physician's otoscope designed for the plasma treatment of OM is shown in Fig. 1, delivering low temperature plasma to the exterior surface of the human eardrum. Several prototypes have been constructed and tested, including the earbud version illustrated at lower-right in Fig. 1.

A follow-on set of *in vivo* experiments is now underway. The accepted animal model for the human ear is the chinchilla, and current tests with two chinchillas are confirming the results of earlier experiments – specifically, that artificially-induced infections in the chinchilla ear are suppressed or eliminated when plasma is introduced to the exterior face of the chinchilla eardrum. If expanded animal studies corroborate these results, clinical studies will be undertaken but the implications of the experiments conducted thus far are profound. The plasma treatment of ear infections is a promising, localized treatment alternative to the prescription of antibiotics, offering the prospect for a dramatic reduction in human suffering and cost.

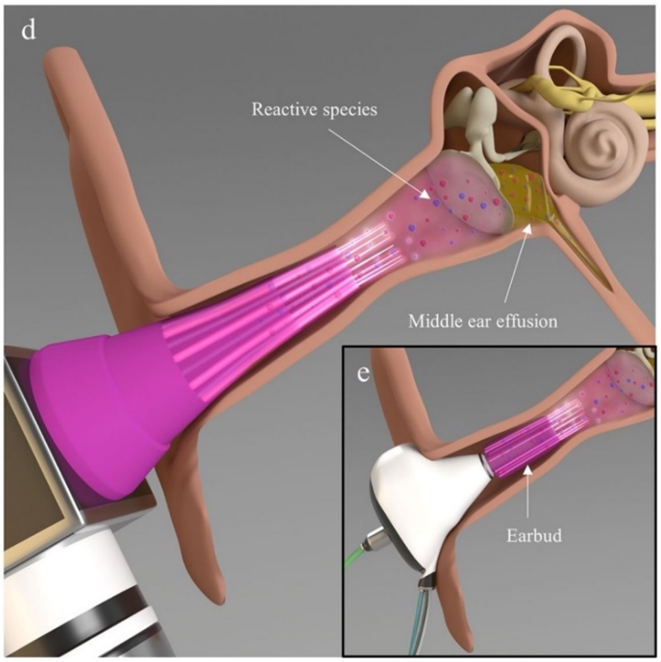

Fig. 1 Illustration of a modified physician's otoscope delivering low-temperature plasma in proximity to a human eardrum. Tests show that reactive species produced within the atmospheric-pressure plasma are able to traverse models of the thin human eardrum and deactivate OM-causing bacteria within a biofilm. (Figure modified from Fig. 7 of P.P. Sun *et al., npj Biofilms and Microbiomes* 7, 48 (2021); reprinted by permission).

Another recent reminder of the potential benefit of plasma science and technology to human welfare is the disinfection of drinking water in off-grid communities in the developing world. Millions of individuals worldwide do not have access to clean drinking water and, accordingly, the National Academy of Engineering (U.S) has identified this human necessity as one of its *Grand Challenges* for the 21st century. Over the past >8 years, advances in microcavity plasma technology have begun to address this critical need in villages and other communities worldwide that do not have access to conventional water disinfectants such as chlorine. Specifically, compact ozone generators commercialized in the last decade are now able to produce 0.3 grams of ozone per hour from humid room air. Since ozone is the most powerful disinfectant available commercially, this production rate is sufficient to quickly eradicate common pathogens (such as *E.coli*) in badly-contaminated river or surface water. Furthermore, the modest power consumption of microplasma generators allows for multiple unit systems to be solar-powered.

Figure 2 is a photograph of a small drinking water disinfection facility in northern Nigeria where access to clean water was unavailable previously. Installed originally to provide disinfected water for surgical irrigation in a small local hospital, systems such as that of Fig. 2 are now providing drinking water in villages and a refugee camp. Larger facilities have also been operational for the past several years in the Kisumu region of western Kenya where two "kiosks" are each producing more than 2000 liters of clean water each day from contaminated river and surface water sources. These village-scale systems, built by a team from the University of Illinois at Chicago in partnership with the Safe Water and AIDS Project (SWAP) of Kenya and the Eden Park Foundation, are operated and managed solely by Kenyans. Through the sale of other products such as plant seedlings, these facilities are economically self-sustaining. Similar projects are in the early stages elsewhere.

Fig. 2 A small drinking water facility in northern Nigeria, representative of multiple similar facilities in the same region. Ozone is generated by microplasma units, one of which is visible (orange box), and powered by small solar panels (not shown). Each of the microplasma generators is robust and easily repaired in the field with "snap-in" replacement parts.

Each of the above examples attests to the enormous potential of low temperature plasma technology in addressing the most basic needs of humanity worldwide. Space limitations preclude the discussion of other efforts such as plasma-based processes for the preservation of fruit, vegetables, and fish, for example, or systems that inactivate *Legionella* in commercial water distribution systems, but suffice it to say that the past 5-10 years have witnessed a surge in the development of sustainable plasma tools to improve the quality of life for those that have restricted or no access to basic necessities. Other challenges, such as the efficient and environmentally-sound disposal of human and animal waste, remain to be overcome but the successes to date are those of which the entire plasma community can be proud.

Text and images by G. Eden and S-J Park; Edited by M. Laroussi

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ABOUT THE AUTHORS

J. Gary Eden has served as a member of the faculty of the University of Illinois (Urbana) for 43 years. After receiving the Ph.D. degree in Electrical Engineering in 1976, he conducted research in the Optical Sciences Division of the U.S. Naval Research Laboratory (Washington, DC). From 1976 to 1979, he co-discovered several lasers, including the KrCl (222 nm) laser and the first proton beam-pumped lasers (Ar-N_2, XeF). Since joining the faculty of the University of Illinois in 1979, he and his students have pursued the science and technology of microcavity plasma devices, atomic, molecular and ultrafast laser spectroscopy, and optical physics in atoms and small molecules. He is currently the Intel Alumni Endowed Chair Emeritus in the Department of Electrical and Computer Engineering (ECE) at UIUC. Sixty-three individuals have received the Ph.D. degree under his direction, and his current research focuses on plasma photonic crystals, ultrafast optical physics such as the control of atomic coherences, laser fractal modes, and VUV photochemistry in the solid state. He was elected to the National Academy of Engineering in 2014.

Sung-Jin Park is a co-Founder and the Chief Technology Officer (CTO) of Eden Park Illumination, and serves as an adjunct member of the Department of Electrical and Computer Engineering faculty at the University of Illinois, Urbana-Champaign. Over the past 23 years, he has developed a series of microplasma technologies including flat, deep-UV/VUV lamps, nanofabrication deposition and etching processes, water purification systems, and lamps for atomic clocks. In addition to Eden Park Illumination, Dr. Park is the co-Founder of EP Pure (formerly EP Purification), Cygnus Photonics, and EPL Power Electronics for the commercialization of microcavity plasma technology. In 2019, Drs. Park and Eden co-founded the Eden Park Foundation for the purpose of providing solar-powered, point-of-use systems offering clean drinking water to off-grid communities in the developing world.